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Application of decision tree and discrete wavelet transform for an optimized intelligent-based islanding detection method in distributed systems with distributed generations

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A R T I C L E I N F O

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In this paper, a method for islanding detection based on analysis of transient state signals is provided. Decision tree (DT) is trained for classifying the transient events. The required features for classifying are extracted through discrete wavelet transform (DWT) of signals. The proposed method is then simulated on a medium voltage distribution system of CIGRE with two kinds of distributed generations (DGs) using DIgSILENT, MATLAB and WEKA softwares. By analysis performed on type of input signal, type of mother wavelet and required transform level, among 162 relay designs, an optimum relay is selected for distributed generations (DGs) based on accuracy, speed, simplicity and cost parameters. By evaluation, it is determined that using only one input (voltage) signal not only improves speed and simplicity and reduces costs, also makes accuracy of the proposed relay better than other intelligent and passive methods. The final selected relay for each DG is V-db4-D3 which has accuracy equal 98%.

Contents

1. Introduction

Recently, due to environmental pollution and the immanent exhaustion of fossil fuel, distributed generations (DGs) using renewable energy sources, including wind power, micro hydro, solar photovoltaic and landfill gas, have become one of the main power generations. Islanding detection is an important protection to consider when distributed generation (DG) is connected to distribution systems.

Islanding takes place when a part of the network becomes disconnected from the grid, and is powered by one or more DGs only. The system in Fig. 1 contains the utility system on the left and the DG fed distribution system on the right. There are various customer loads

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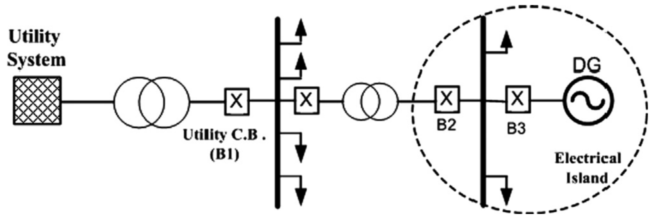

Fig. 1. A general view of electrical islanding.

between these two electrical power sources. The essential task of an islanding detection protection is to find accurately the time of islanding event and to disconnect the DG.

Islanding is an undesirable situation since it is a potentially dangerous condition for the maintenance personnel and may cause damage to the DG and loads in the case of unsynchronized reconnection of the grid due to phase difference between the grid and DG [1]. Therefore, it has become a mandatory feature specified in the IEEE Std. 1547.1, IEEE Std. 929-2000, and UL1741 standards.

Islanding detection techniques can be divided into remote and local ones, whereas the local techniques are divided into passive and active ones. Hybrid methods combine the effectiveness of passive and active approaches and can be applied as an alternative. Remote techniques such as power line communication (PLC) [2], supervisory control and data acquisition (SCADA) [3], transfer-trip [4] are based on communication between the grid and the DGs. They have better reliability than local techniques but are more expensive.

Active detection methods, deliberately introduce perturbations into the system. In the loss of grid situation, however, small deviations will be amplified by positive feedback and, hence, it becomes easy to detect the islanding condition. Some active islanding detection methods that have been proposed include active frequency drift (AFD) [5], slip-mode frequency shift [6], automatic phase shift [7], sandia frequency and voltage shift [8], reactive power export error detection [9], system fault level monitoring [10] and phase-locked loop (PLL) perturbation, system input impedance [11] methods. The main advantage of active methods is their relatively small NDZ. The main disadvantage, however, is power quality problems due to their direct influence on the power system.

Passive techniques rely on monitoring the power system's behavior by measuring system parameters. This is an advantage but many other non-islanding disturbances will produce transients that mimic very closely to those of an islanding event. For this reason, thresholds on measured parameters (for example, frequency or voltage) are set wide, but it results in large non-detection zone (NDZ) [12]. Passive techniques include over/under voltage and frequency (OVP/UVP and OFP/UFP) [13], rate of change of frequency with time (ROCOF) [14], rate of change of power with time [15], rate of change of frequency with power [16], and total harmonic distortion (THD) and voltage unbalance [17], phase jump detection [18], comparison of ROCOF (COROCOF) [19], inter-tripping [20], fault thrower and neutral voltage displacement (NVD) [20], rate of change of voltage and power factor [20], elliptical trajectory technique [20], rate of change of phase angle difference (ROCPAD) [21] and fuzzy rule [22].

Passive techniques do not have power quality problems and are generally quite cheap to install but they have large NDZs. However they cannot ensure guaranteed operation under all islanding situations [20].

Classification-based techniques have been recently proposed in the literature for islanding detection. An intelligence-based method is investigated in Ref. [23], which uses the decision-tree (DT) classifier, but with complex set of 11 features for classification, including total harmonic distortion of current/voltage, gradient of the product of voltage and power factor, etc. It has only 83.33% islanding detection accuracy. A hybrid islanding detection algorithm based on wavelet transform is discussed in Ref. [24], but it is specifically for single-phase photovoltaic (PV) DG systems. The method based on wavelet transform and DT classifier presented in Ref. [25] could obtain 96.43% accuracy by using fourth level of discrete wavelet transform (DWT) but with both two signals current and voltage. Accuracy of other passive methods that are summarized in Ref. [26] is lower than this value.

In some papers [27,28], the absolute value of certain wavelet coefficient of voltage or current or frequency, are compared against a threshold value; and if the relevant wavelet coefficient remains above this preset threshold for a certain time, an islanding condition is declared. These system specific threshold values are determined through trials based on the experience of utility engineers [28]. Some papers [29–32] without any reason or proof have used a certain signal (voltage or current or both) or specific mother wavelet or certain level of wavelet transform even with high levels 6th and 7th [31,32]. Some papers [25,26] have followed results which presented in Ref. [29]. In Ref. [29], a specific mother wavelet and certain level of wavelet transform have been proposed by analyzing only short circuit conditions on a simple system consisted of two generators and one distribution line. Whereas the real distribution system is more complex and its transient events are more varied. As a result it is necessary the mother wavelet and levels of DWT are selected with more precision and evaluation. In some other papers [29,30], few cases of transient scenarios were tested and comprehensive assessment has not been on the proposed algorithm.

In this paper, it is attempted through study and analysis of a real distribution system, an optimum algorithm with higher accuracy and speed (lower computation) than previous techniques is obtained. Instead of using (1) both voltage and current signals or (2) complex set of parameters, or (3) the threshold values determined through trial and error and (4) high level of DWT and (5) certain mother wavelet and DWT levels, it analyses different mother wavelet, DWT levels and input signals, uses lower DWT level and only one transient signal (voltage) generated during the disconnection of the grid. The method involves extraction of signal energies in different levels of DWT as features. It uses decision tree (DT) as a classifier in identifying the islanding condition.

The rest of the paper is organized as follows: Section 2 provides the theory of the DWT and DT. The case study is introduced in Section 3. Section 4 presents the proposed islanding detection method. Section 5 provides the simulation. The last section touches upon the conclusion.

2. DWT and DT

Voltage and current transient signals of a power system are believed to have unique characteristics that signify the cause of transient event. The method proposed here is based on this fact that transient state has certain characteristics which can be used to present a new method to distinguish the island occurrences from the other ones. Of course the features presented in transient signals are not directly diagnosed. So there should be a process to extract these features to speed up response in classifying. To this end, wavelet transform seems to be suitable.

Some important classification methods include support vector machines, neural network and decision tree. Although studies have been carried out to compare them [32], due to a number of factors and possibilities, we cannot definitely state which method

has a preference in every way. The method proposed uses DT for pattern recognition and classification.

2.1. Features extraction by DWT

DWT is used as a means for processing of transient signals. Using DWT, a signal can be decomposed into some signals in different frequency bands which are known as wavelet coefficients. It is more suitable for analysis of transient states in comparison with other frequency methods such as Fourier transform (FT). A suitable study of Fourier and wavelet transforms can be obtained in Ref. [33]. DWT of a signal $f(k)$ is defined in mathematical relations (1) and (2) as

$$DWT_{\psi}f(m,n) = \sum_{k} f(k)\psi^{*}_{m,n}(k) \tag{1}$$

where $\psi_{m,n}$ discrete mother wavelet is defined as follows:

$$\psi_{m,n}(k) = \frac{1}{\sqrt{a_0^m}}\psi\left(\frac{k-nb_0a_0^m}{a_0^m}\right) \tag{2}$$

$a_0\ (>1)$ and $b_0\ (>0)$, are the fixed real values and m and n are the positive integer numbers.

DWT breaks down a signal to an approximate (A) and a detail (D). The approximate is again breaded down in order to obtain the next level information and this trend will continue. Each level i consists of $j=2^i$ wavelet translated and equally spaced $2^M/j$ intervals apart; that 2^M is the number data points of the signal and M is an integer. Thereby, increasing the decomposition levels also increases detection time [34]. In each level of this decomposition, to increase the frequency resolution, the parameter m in Eq. (2) is increased. In fact, the main signal by passing through two high pass and low pass filters will be decomposed in two signals as approximate (A) and detail (D) which are shown in Fig. 2.

2.2. Decision tree (DT) based classifier

Pattern recognition is a learn-by-example mathematical tool, which is extremely useful for those problems that cannot be solved with analytical methods. DT is a type of pattern recognition tool, and is capable of classifying input vectors into discrete categories such as {0, 1}. It is based on the principle that many separation boundaries can be approximated by combinations of hyper-planes that are parallel to the coordinate axes. Therefore it can break down a complex decision-making process into a collection of simple decisions [35]. The main advantage of DT is fast training compared with other popular pattern recognition tools. DTs are widely used in many diverse areas.

A decision tree can be learned by splitting the source feature set into subsets. This process is recursively repeated on each derived subset. For instance, Fig. 3 shows a possible binary partitioning using hyper-planes perpendicular to the feature axes of the space with three classes, W1–W3 and two features, X1 and X2. Fig. 4 indicates corresponding decision tree; both provide 100% correct classification of the labeled samples. All the interior nodes

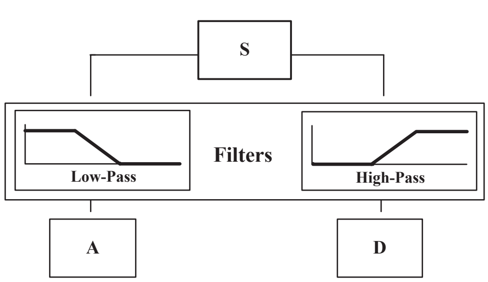

Fig. 2. A general view of wavelet transform, a decomposition filter.

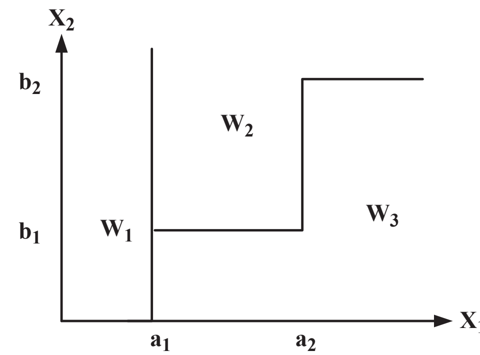

Fig. 3. Feature space.

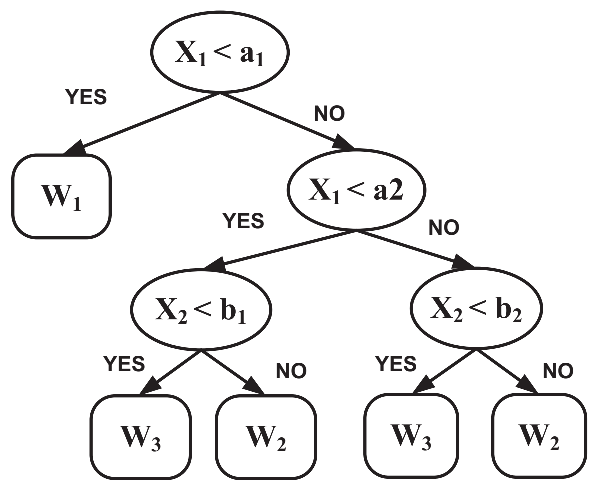

Fig. 4. Decision tree.

correspond to the features and arcs to the child give possible values of each feature. The predicted class of a target feature is represented by a leaf of the tree. The depth of a node is the length of the path from the root to the node.

In a decision tree for each node m, N_m instances reach m and N_{im} of then belong to C_i. Eq. (3) represents this relation.

$$P(C_i|X,m) \equiv p^i_m = \frac{N^i_m}{N_m} \tag{3}$$

Node m is pure if p^i_m is 0 or 1. If node m is pure, generate a leaf and stop, otherwise split and continue recursively. The measure of impurity is entropy. The C4.5 algorithm uses the concept of information gain or entropy reduction. Variable X whose k possible values have probabilities to p_1, $p_2 \ldots p_k$. Entropy of variable X is

$$H(X) = -\sum_{j} p_j \ \log_2^{p_j} \tag{4}$$

Candidate split S, which partitions training set T into several subsets, T_1, $T_2 \ldots T_k$.

$$H_S(T) = \sum_{i=1}^{k} P_i H_s(T_i) \tag{5}$$

Information gain for variable S is Gain(S)=$H(T)-H_S(T)$

At each decision node, C4.5 chooses the optimal split to be the split that has the greatest information gain, Gain(S).

2.3. Cross validation

There are variants of cross-validation (a standard tool in statistics) that find their own uses in practice. We use multifold

cross-validation by dividing the available set of N examples into K subsets, $K>1$. In this case, $K-1$ subsets are used to train the model, and the validation error is measured by testing it on the subset left out. This procedure is repeated for K trials, each time using a different subset for validation. The performance of the model is assessed by averaging the squared error under validation over all the trials of the experiment.

3. Proposed algorithm

Transient events in power systems are usually non-periodic, short-term and non-stationary waveforms. Wavelet transform can decompose signals into various frequency bands. DWT of transient signals of current and voltage is used to derive features vector needed for classification. The goal of feature derivation is to determine unique characteristics of current and/or voltage waveforms that can be used for distinguishing between islanding situation and other situations.

In this article, in order to obtain a relay with maximum speed and precision, some widely-used mother wavelets from Daubechies family, including db1, db4 and db7, are examined. Basically, due to similarity of mother wavelets, db1 can be considered representative of db1–db3, db4 can be considered representative of db4 to db6 and db7 can be considered representative of db7 to db10.

Signals in each mother wavelet are decomposed up to 9 levels to select wavelet level in order to obtain the best efficiency of relay. Sampling frequency is 10 kHz. Information of frequency bands of wavelet transform is presented in Table 1.

In order to obtain an optimized relay, detail coefficients energy of DWT of current and/or voltage signals is applied to DT classifier as the feature vector. Energy is obtained according to relation (6)

$$E_{m,v_a} = \left[\sum_k d_{m,k}^2\right]^{1/2} \tag{6}$$

E_{m,v_a} is the energy of mth level of DWT of voltage phase-a (v_a). $d_{m,k}$ is the kth coefficient of mth level. Schematic diagram of the proposed method, including features extraction and application to DT classifier to ninth level of voltage signal, is shown in Fig. 5. Also three phases of DG currents should be added to Fig. 5. The features are fed to a trained DT that can distinguish islanding events from other events such as switching or transient faults.

In this article, different states and structures of the studied system are simulated in DIgSILENT software and current and voltage of DGs are recorded. Then, by programming in MATLAB software, wavelet coefficients of current and voltage of DGs in levels 1–9 are calculated with three different mother wavelets as features needed for classification. Eventually, features belonging to various events are applied to DT created in WEKA software and accuracy of the design is calculated. Today WEKA is known as a landmark system in Machine Learning and Data Mining systems in scientific and commercial areas [36].

In order to obtain optimum relay in terms of accuracy, speed, cost and simplicity, proposed designs are examined from three aspects:

1) selection of appropriate signal applied to relay:

Table 1
Frequency bands of different levels of DWT.

Level	Frequency bands (Hz)	Level	Frequency bands (Hz)
D1	2500–5000	D6	78.125–156.25
D2	1250–2500	D7	39.0625–78.125
D3	625–1250	D8	19.53–39.0625
D4	312.5–625	D9	9.765–19.53
D5	156.25–312.5	A9	0–9.765

- relay decides only based on voltage. This type of relay is designated by (V).
- relay decides only based on current. This type of relay is designated by (I).
- relay decides based on both current and voltage. This relay is presented by (VI).

2) the above-mentioned relays were studied with three different mother wavelet db1, db4 and db7 of Daubechies family.
3) the above relays were evaluated at levels 1–9.

4. Case study

The studied network is the CIGRE medium voltage distribution system which is extracted and introduced from medium voltage distribution network of Germany by CIGRE Association for performing comprehensive studies on behavior of systems with DG. This network is shown in Fig. 6. Structure of real network includes 30 nodes, which is presented in Ref. [37]. The number of nodes has been reduced by CIGRE in order to reduce network size to an acceptable level for performing DG studies. Rated voltage level of

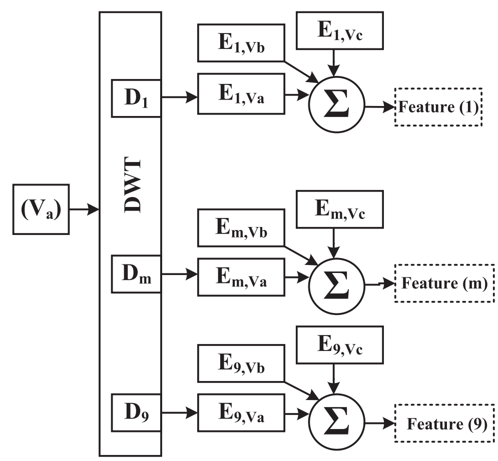

Fig. 5. The extraction method of required features for classification of events.

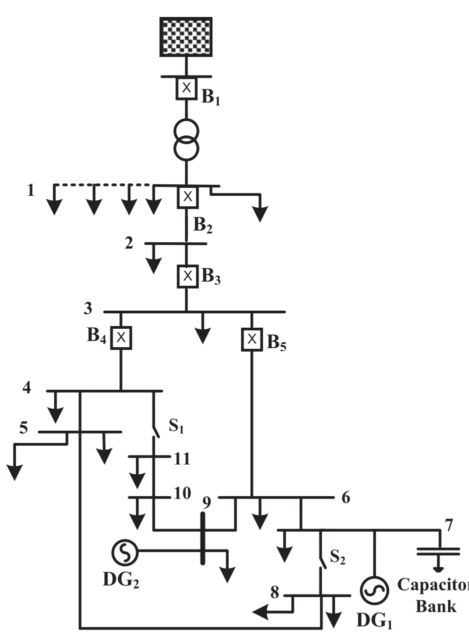

Fig. 6. The CIGRE medium voltage distribution system.

the network is 20 kV which is fed through a transformer from 110 kV network.

This distribution system has two DGs: one with induction generator (DG1) with 1.5 MVA capacity, connected to bus no. 7 along with 0.48 MVAR capacitance compensator and the other one with synchronous generator (DG2) with 1 MW and 100 kVAR capacity, connected to bus no. 9. All network loads are considered impedance. The system has two keys S1 and S2, which makes it possible to change network structure from radial to ring operation.

In this paper, information is collected in four different structures through opening and closing keys S1 and S2. In addition, two states are considered in each structure: matched power and mismatched power. So totally there are 8 states. One of the most difficult states in detection of islanding is matched power state (zero load flow from island toward network and vice versa). When islanding phenomenon occurs in matched power state, electrical quantities especially frequency and voltage are quite low and cause elimination of some signal features, which can cause problems in detection of this phenomenon. This paper aims to present an islanding detection method that can perform well under zero load flow and other operation conditions.

Events are categorized into two groups: non-islanding and islanding events. In the studied network, various events are simulated in 8 states of network. Non-islanding events include

(1) normal operation, (2) four types of transient fault, including three-phase, two-phase, two-phase to earth and one-phase to earth in all 11 bus bars, (3) switching of all loads, (4) switching of DGs, (5) switching of capacitor.

Islanding events include

(1) opening of breakers B2 and B3 after occurrence of any of four types of faults on bus 2, (2) opening of breakers B3, B4 and B5 after occurrence of any of four types of faults on bus 3, (3) opening of breakers B4 and B5, (4) opening of breakers B3, B4 and B5, (5) opening of breaker B1, (6) opening of breaker B2, (7) opening of breaker B3.

5. Results of simulation

Fig. 7a shows currents and voltages of 3-phases of DG1 and Fig. 7b–j shows wavelet coefficients of first to ninth levels. It is corresponding to a non-islanding event. The event is one of 568 simulated samples related to three-phase short circuit at

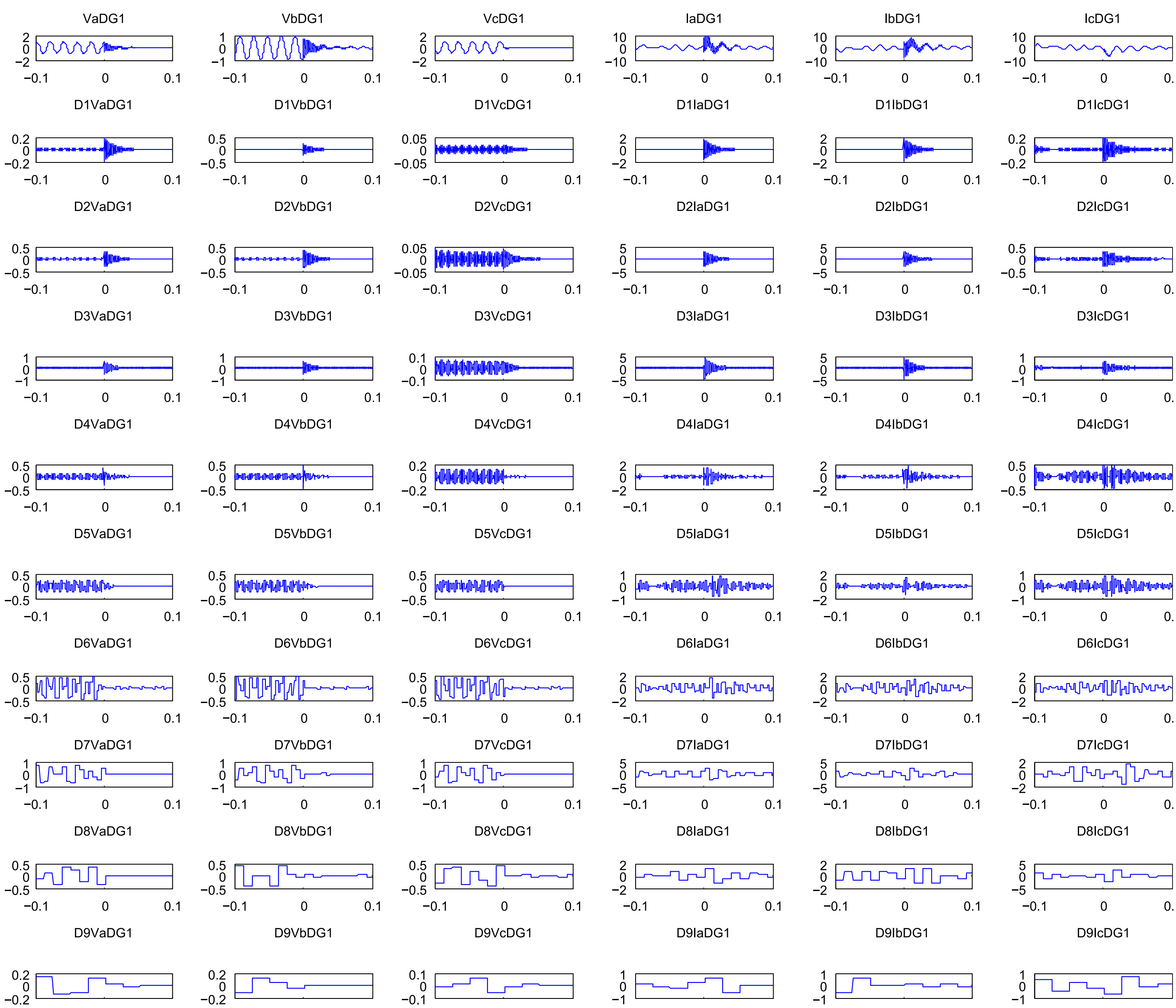

Fig. 7. (a) Current and voltage waveform of DG1, (b–j) wavelet transform of their first to ninth levels.

zero-instance in bus no.11. In 568 events mentioned, waveforms similar to Fig. 7 are recorded and calculated for DG1 and DG2.

Table 2 presents accuracy of different designs obtained from the proposed algorithm.

First column represents the corresponding DG. Second column shows the type of mother wavelet. Third column presents relay input. Terms V, I and VI represent relay inputs which are described at the end of the fourth section. Columns 4–12 show relay accuracy at first to ninth levels of DWT.

5.1. Evaluation of relays from input signals point of view

In the first stage, in order to obtain optimum relay, we evaluate relays in terms of input signals to determine which signal is more effective in islanding detection. To this end, we divide results of Table 2 into three groups separately for DG1 and DG2 namely (V), (I) and (VI). As can be seen from Fig. 8, at levels 1–9, relays of DG2 that work with only current signal (I) do not have acceptable accuracy and are lower than the other two types at all levels.

At all levels, average accuracy of VI is equal to V, so that curves of V and VI types are overlap. Certainly, in identical conditions, in order to reduce computational costs, increase decision speed and make relays simpler, using relays V is preferred to relays VI.

5.2. Evaluation of relays in terms of mother wavelet

In this stage, in order to select the optimum mother wavelet, we divide initial results of Table 2 into three groups separately for each DG with mother wavelets db1, db4 and db7. The average accuracy of each group at first to ninth levels is showed in Fig. 9.

By evaluating Fig. 9a, we find that accuracy of three types of mother wavelets in DG1 are nearly identical but Fig. 9b shows that for DG2, accuracy of db1 is lower than that of the other two types.

At almost all levels, average accuracy of db4 is equal to db7, so that curves of db4 and db7 types overlap. Certainly, in identical conditions, in order to reduce computational costs, as a result increase decision speed, using relays db4 is preferred to relays db7.

5.3. Selecting optimum relay for DGs

By considering provided diagrams and presented explanations, we are going to select the best relay for DGs in this section. Based on Section 5.1, relay type (I) is eliminated from discussion and selection and only relays (V) and (VI) remain. According to Section 5.2, mother wavelets db1 and db7 are eliminated from competition.

In Table 2, relays V and VI with mother wavelet db4 that both DGs have 97% or higher accuracy are shown in gray. But among gray cells, relays V and VI have identical accuracies. Due to simplicity, lower costs and higher speed of relays fed with one signal, relays type V compared to type VI are selected. For obtaining maximum speed in selected relay, the lowest level among gray cells, namely the 3th level, is considered. Therefore, the final selected relay for each DG is V-db4-D3 which is bolded among gray cells.

5.4. Comparison of results with valid papers

The intelligent method presented in Ref. [23], in spite of using a complex set of features with DT classifier, only has 83.33% accuracy. Some papers [24–26] have used a certain signal (voltage or current or both) or a specific mother wavelet [27,28] or certain level of DWT or with high levels of DWT [29–32] without any

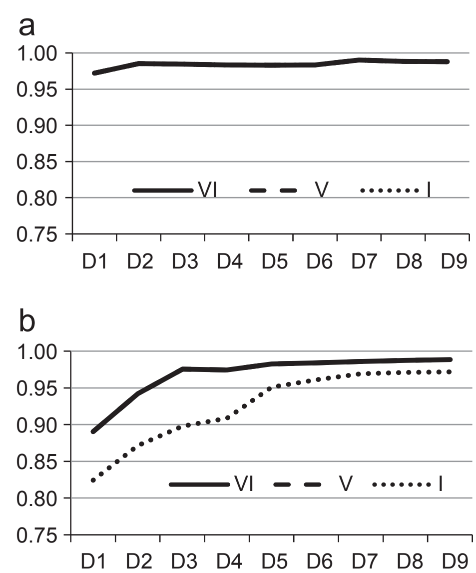

Fig. 8. Average accuracy of relays on the basis of input signals, (a) DG1, (b) DG2.

Table 2
Accuracy of studied relays.

DG	Mother wavelet	Relay input	D1	D2	D3	D4	D5	D6	D7	D8	D9	Average
DG1	**db1**	**VI**	0.98	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.99	0.99
		V	0.89	0.95	0.96	0.97	0.98	0.98	0.99	0.99	0.99	0.97
		I	0.95	0.95	0.96	0.97	0.98	0.98	0.98	0.98	0.98	0.97
	db4	**VI**	0.97	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.98	0.98
		V	0.74	0.95	0.98	0.98	0.99	0.98	0.99	0.99	0.99	0.96
		I	0.95	0.97	0.97	0.98	0.99	0.99	0.98	0.98	0.98	0.98
	db7	**VI**	0.97	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.98
		V	0.83	0.94	0.98	0.98	0.98	0.98	0.99	0.98	0.99	0.96
		I	0.95	0.95	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.97
DG2	**db1**	**VI**	0.89	0.93	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.96
		V	0.88	0.94	0.96	0.97	0.97	0.98	0.98	0.98	0.98	0.96
		I	0.84	0.82	0.83	0.85	0.89	0.93	0.96	0.96	0.96	0.89
	db4	**VI**	0.90	0.95	0.98	0.97	0.98	0.98	0.99	0.99	0.99	0.97
		V	0.67	0.90	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.94
		I	0.80	0.90	0.93	0.95	0.98	0.97	0.97	0.97	0.98	0.94
	db7	**VI**	0.89	0.94	0.98	0.97	0.99	0.99	0.99	0.99	0.99	0.97
		V	0.79	0.90	0.97	0.97	0.99	0.99	0.99	0.99	0.99	0.95
		I	0.83	0.89	0.93	0.94	0.98	0.98	0.97	0.98	0.98	0.94

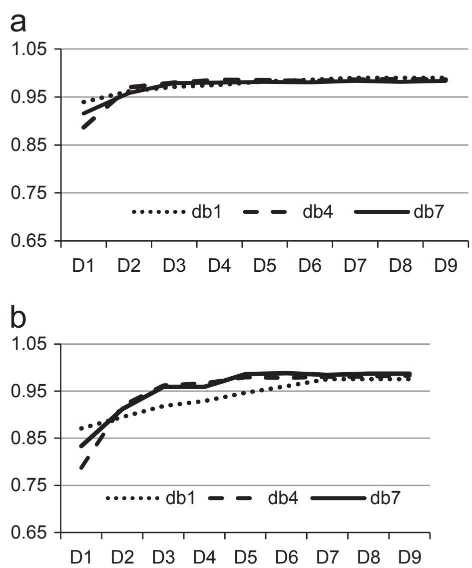

Fig. 9. The average accuracy of relays based on the type of mother wavelet, (a) DG1, (b) DG2.

Table 3
Accuracy of several passive islanding-detection relays.

Other passive methods	Accuracy (%)
Over/under voltage [26]	78.81
Over/under frequency [26]	90.24
Voltage vector shift (VVS) [26]	74.05
Rate of comparison of frequency (ROCOF) [26]	93.81
DT classifier based relay [25]	96.43
Intelligent-based relay [23]	83.33
Proposed relay	98

reason or proof. In this article, it is attempted through analysis to obtain an optimum algorithm.

The method based on wavelet transform presented in Ref. [26] could obtain 96.43% accuracy by using fourth level of DWT of both current and voltage signals. Maximum accuracy of other passive methods that are summarized in Table 3 is lower than these values [26]. But the relay proposed in this article could obtain higher accuracy (98% and higher) by using only one signal and 3th level of DWT. The proposed relay has higher accuracy and has become simpler, faster and less expensive because of using only one signal and lower number of decomposition levels.

5.5. Flowchart algorithm of final selected relay

Based on simulation results and analysis and evaluations done, flowchart of algorithm of the proposed relay is shown in Fig. 10. By sampling frequency of 10 kHz, one cycle includes 200 samples. Feature vector, including samples of energy of wavelet transform coefficients of voltage signal of DGs with mother wavelet db4 and 3th level of wavelet transform is fed to DT for training. Determination of whether islanding has occurred or not is performed by help of trained DT.

Table 4 lists the parameters and detail results of the DT of proposed algorithm. Fig. 11 indicates the tree of the proposed algorithm.

6. Conclusions

In this article, a method of electric islanding detection based on analysis of transient state signals of DGs during islanding and non-islanding events using DWT and DT is provided. By analysis performed on type of input signal, type of mother wavelet and required transform level, among 162 relay designs, an optimum relay was selected for each DG based on accuracy, speed, simplicity and cost parameters.

The selected relay with voltage signal input, mother wavelet db4 and 3th level of transform has 98% accuracy for DG1 and DG2 (V-db4-D3). Given the sampling window length that is considered to be 0.01 s, relay performance speed can be estimated lower than one cycle. By evaluation, it was determined that using only one input signal (voltage) in addition improves speed and simplicity and reduces costs, also makes accuracy of the proposed relay better than similar methods and other passive methods.

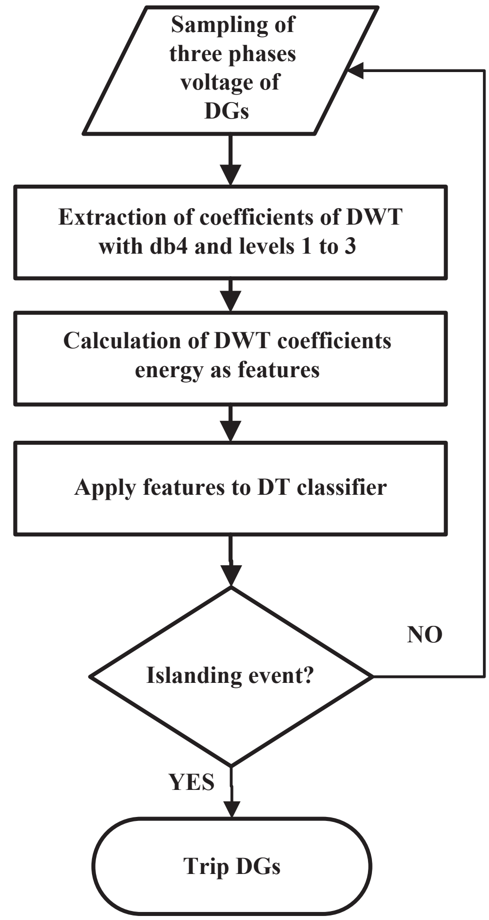

Fig. 10. Flowchart of the proposed algorithm.

Table 4
Parameters and detail results of the proposed algorithm.

DT parameters	
Confidence factor	0.25
Min_Num_Obj	2
Num_Folds	3
Multifold cross validation	$K=10\%$
Details of DT results	
Number of leaves	8
Size of tree	15
Correctly classified instances	558
Incorrectly classified instances	10

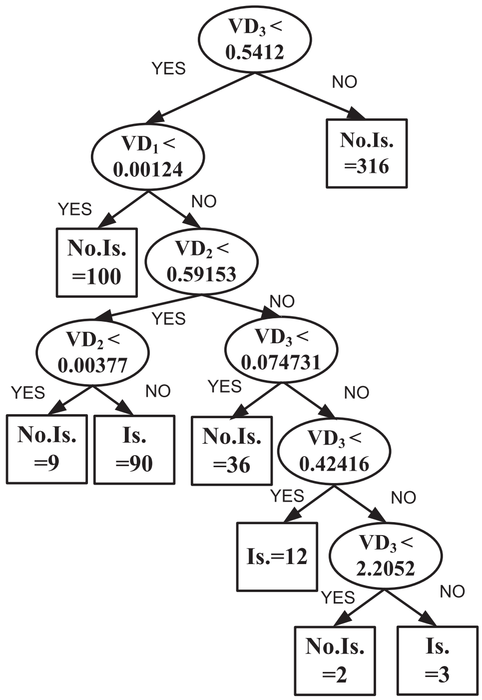

Fig. 11. Tree of the proposed algorithm (Is.=Islanding, No.Is.=Non-Islanding).

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